TO: J. MENARD
FROM: M.L. REINKE
SUBJECT: GOALS FOR FY18 R18-1/PCRF-WG

In order to better organize and coordinate activities that will be completed as part of the PFCR Working Group and the R18-1 NSTX-U Research Milestone, the following list of goals is presented. This is intended to be an ambitious list of activities and I expect the resources will not be available to complete 100% of this work. Updates and changes will be summarized at ~monthly PFCR-WG meetings and at quarterly NSTX-U Milestone meetings. We will use this structure to update and redirect as needed. Late in FY18, results will be able to motivate possible continuation or new FY19 Milestone/PFCR-WG activities.

The R18-1 Milestone Text (below) is broken up into three sub-categories and then further broken into specific goals, which have 'leads' and 'deliverables' along with a brief description.

R(18-1): Develop and benchmark reduced heat flux and thermo-mechanical models for PFC monitoring

Description: The NSTX-U Recovery Project will deploy new plasma facing components (PFCs) to meet updated heat exhaust requirements driven by narrower scrape-off-layer widths, increased heating power, and longer pulse durations relative to NSTX. Inter-shot monitoring or intra-shot control of heat flux to PFCs is anticipated for a range NSTX-U operating space, necessitating reduced models that can be run between shots or even in real-time. Monitoring requires a reliable instrumentation suite which can support or contradict model predictions and confirm PFC integrity. The goals of this milestone are three-fold: (1) Develop tools for pre-shot planning and confirmation of post-shot PFC thermal observations which use reduced models to predict time-evolving heat fluxes to shaped PFCs and estimate distances from engineering limits. Assess additional effort needed for implementation of reduced models in PCS. (2) Where feasible, benchmark reduced models against boundary physics (e.g. SOLPS, UEDGE) and finite element analysis (e.g. ANSYS) tools, and validate using experimental data from relevant tokamaks and results from Facility Milestone F(18-1). (3) Evaluate examples of discrete monitoring systems that are sufficient to capture the evolution of the PFCs relative to engineering limits. Compare the ability for different techniques (e.g. thermocouples vs. imaging) and technologies (e.g. near vs. long-wave infrared cameras) to achieve NSTX-U PFC monitoring objectives.

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GOAL 1: Evaluate and demonstrate tools for efficiently computing heat flux from axisymmetric plasmas onto non-axisymmetric plasma facing components.

Lead: ORNL (TBD – Reinke for now)

Deliverable: NSTX-U Report/Plan discussion options for assessing heat flux to shaped PFCs

Description: The present state of modeling heat flux for planned NSTX-U plasmas is W_PFC which assumes axisymmetric PFCs and an axisymmetric heat flux from the plasma. Real PFCs will be non-axisymmetric due to intended surface shaping (e.g. 'fishscaling'), uneven interfaces (e.g. IBDH/OBD) or faceting of mounting structures (OBD). As part of long-term scenario planning and inter-shot, inter-run evaluation the ability to generate detailed heat flux to 3D PFCs is expected to be an important capability for NSTX-U commissioning. Several existing tools (PFC Flux, SMARDDA, Div3D) should be investigated to understand an appropriate choice for NSTX-U needs. Work should test these tools for NSTX-U designs and equilibrium and comment on the fidelity and speed of results and necessary enhancements needed for NSTX-U.

GOAL 2: Develop and test initial 'pre-shot' heat flux control simulations, extending existing PCS tools

Lead: PPPL (Boyer w/ Battaglia)

Deliverable: A code to produce W_PFC input data (G-EQDSK, ASCII driver, etc.) from heat flux control requests.

Description: Within R18-1/1 (R18-1/1-G4), the basic logic on how to perform simultaneous control of various equilibrium parameters for heat flux control will be derived. This GOAL is to interface that work with existing control simulation frameworks using in the PCS group. A mechanism is needed to take a target plasma (prior shot, TRANSP simulation, etc) and a control request and output time-evolving equilibrium. This will be linked to W_PFC (or equivalent) and be used to predict time-evolving heat flux to the all the PFC regions, allowing calculations of peak surface temperature using ANSYS or reduced models. This tool will be used to develop more accurate demonstrations of heat exhaust control in planned long-pulse scenarios relevant to the 2 MA, 1 T, 10 MW, 5 s mission and demonstrate the ability to pre-program efficient strike point sweeping to reduce time-averaged surface heat flux using a variety of inner PF coils within their design limits.

GOAL 3: Develop and test initial 'post-shot' heat flux summary tool

Lead: ORNL (Reinke)

Deliverable: A code that can calculate the calculate the expected heat flux to PFC surfaces based on post-shot available data (e.g. EFIT, MDS+ time histories)

Description: The present status of the heat flux to axisymmetric PFCs (W_PFC), developed for input into the PFC Requirements, uses a CSV file of existing G-EQDSK files. For use with NSTX-U shots, this should read standard EFIT time histories along with achieved NBI, RF and Ohmic input power and some estimate/approximation of the radiated power. This can be used to calculate achieved peak surface temperature or embedded sensor temperatures using ANSYS or reduced models. This is likely to be an enhancement to the existing W_PFC code base.

GOAL 4: Determine feasibility of PCS control for dedicated heat flux application

Lead: PPPL (Boyer)

Deliverable: NSTX-U Report/Plan document outlining findings.

Description: A possible PFC monitoring approach (R18-1/3-G1) would avoid real-time measurement of PFC temperature, but utilize a model, like that in W_PFC, to predict the surface temperature and avoid pre-programmed limits using real-time equilibrium control and knowledge of the input power, and validating the model post-shot using available diagnostics (R18-1/3-G3). Demonstrated shape control on NSTX-U allows for modest accuracy (~cm's) of the strike points, but its accuracy for use in heat flux control has not been assessed. Improvements may needed for more precise control of strike point sweeping over divertor regions and dr_{sep} control for power sharing. A new controller is likely needed to control poloidal flux expansion (e.g. angle of incidence) and understand the correlated impact (e.g. what control is given up to achieve this). Work should develop a scheme for dedicated heat flux control which and show it is feasible within expected NSTX-U coil and magnetics measurements. The PFCR-WG team should coordinate on defining requirements for control and explore how increasing levels of heat flux control limit other equilibrium control options. Additionally, briefly describe resources that would needed for implementation if requested by Recovery in FY19 or beyond.

GOAL 5: Determine necessary PCS enhancements for doing real-time control from imaging systems

Lead: PPPL (Erickson)

Deliverable: NSTX-U Report/Plan document describing necessary PCS enhancments.

Description: The NSTX-U real-time control system is presently designed to handle only voltage time history information from measurements located in the NTC or DARM. Even analysis of CCD image data for CHERS (for RTV), results are converted to analog voltages and re-digitized by the PCS. A possible PFC monitoring approach would require deriving information from multiple camera systems (R18-1/3-G2), for example monitoring a region of interest on a NIR camera for a possible 'hot-spot'. This type of performance has been demonstrated or is planned for metallic wall machines, JET, AUG and WEST. This activity should review existing published or presentation material from one or more of the listed devices and outline the necessary enhancements to the NSTX-U PCS to develop a similar functionality. This information will be used in judging what the necessary work if one or more PFC monitoring approaches are to be implemented in FY19 or beyond. Real requirements for such an imaging monitoring system are expected only after R18-1 activities are complete, but a 'working requirements' draft can be created to help guide progress.

R18-1/2: Where feasible, benchmark reduced models against boundary physics (e.g. SOLPS, UEDGE) and finite element analysis (e.g. ANSYS) tools, and validate using experimental data from relevant tokamaks and results from Facility Milestone F(18-1).

<u>GOAL-1: Export/Extend W_PFC to allow for comparisons to non NSTX/NSTX-U heat flux measurements</u>

Lead: ORNL (Reinke)

Deliverable: A code that can either be run on PPPL computers (e.g. nstxpool, portal) or be deployed on remote servers to compute heat flux for non-NSTX devices.

Description: Presently, and through R18-1/1-G3, W_PFC has only been demonstrated to be functional for NSTX/NSTX-U. In order to demonstrate its accuracy prior to NSTX-U operations, W_PFC (or its replacement) need to be validated on other devices. The basic structure of W_PFC should allow for importation of G-EQDSK files from other devices and the extension to load from local EFIT data can be completed if W_PFC is to be deployed elsewhere. Presently, this is planned only for Alcator C-Mod (R18-1/2-G2), but activity under this goal will support other testing (R18-1/2-G3) as needed.

<u>GOAL 2: Compare W_PFC predictions to Alcator C-Mod measurements</u>

Lead: ORNL (Reinke)

Deliverable: NSTX-U Report describing findings.

Description: Alcator C-Mod experiments from FY15/16 supported research on heat flux profiles in the inner and outer divertor as well as the variation as equilibria were varied from lower to upper single null and near DN. A database describing this effort has been compiled and results are in preparation for submission (D. Brunner). This represents a range of cases for which W_PFC can be tested and model assumptions adjusted or model extended.

GOAL 3: Compare W_PFC predictions to (tokamak/ST to be determined) measurements

Lead: TBD

Deliverable: (same as GOAL 2)

Description: (same as GOAL 2)

GOAL 4: Extend validated high heat flux (HHF) ANSYS simulation to allow for arbitrary surface heat flux as a function of space and time

Lead: ORNL (A. Lumsdaine) w/ PPPL (A. Brooks)

Deliverable: ANSYS Workbench model linked to ASCII or other interchange format from W_PFC or equivalent.

Description: The PFC requirements only represent a small subset of possible time and space evolving heat flux loads that NSTX-U is expected to produce. To better understand the operational constraints of NSTX-U, the detailed thermo-mechanical modeling needs to first be extended to represent realistic NSTX-U heat loads and then a reduced model developed/confirmed (R18-1/2-G5). For the IBDH, IBDV and (resources permitting) OBD-R1/R2 tiles, the ANSYS Workbench model (or equivalent) needs to be improved to allow for the intra-castellation surface heat flux to evolve over space and time. This should be done in an efficient manner to allow for scripting, driven by W_PFC output and (eventually) by the R18-1/1-G1 tools.

GOAL 5: Compare detailed ANSYS model against semi-infinite solid predictions and evaluate role of temperature dependent thermal properties.

Lead: ORNL (A. Lumsdaine) UT-K (T. Looby) and/or ORNL (Gray)

Deliverable: NSTX-U Report describing findings with the goal of testing the semi-infinite solid approximation with temperature independent material properties against ANSYS.

Description: A candidate for a simplified model to predict surface temperature and sub-surface stresses in high heat flux tiles is the semi-infinite solid. This needs to be compared to results of ANSYS simulations for cases of arbitrary time and space evolution surface heat flux. In addition the temperature dependent material properties may also play a role in the accuracy of simplified model predictions, compared to a variety of temperature dependent material property choices. Simple 1D numerical heat flux models in IDL/Matlab are also an acceptable form of reduced model if non-analytical functions for material properties are required. The intent is to have something to service (at least) inter-shot analysis.

R18-1/3: Evaluate examples of discrete monitoring systems that are sufficient to capture the evolution of the PFCs relative to engineering limits. Compare the ability for different techniques (e.g. thermocouples vs. imaging) and technologies (e.g. near vs. long-wave infrared cameras) to achieve NSTX-U PFC monitoring objectives.

<u>GOAL-1: Describe monitoring approach that does not use optical measurements to determine if an NSTX-U discharge is approaching temperature limits</u>

Lead: ORNL (Gray & Reinke)

Deliverable: PFC monitoring plan describing monitoring goals and approach (TCs + bolometry)

Description: In order to hedge against optical (NIR/IR) measurements not being available for NSTX-U operations or not being interpretable during heavily lithiated discharges a non-optical means of PFC monitoring is needed. For this goal, the general approach would be to use real-time knowledge of the equilibrium, the input power and the radiated power to predict time-evolving surface heat flux via the basic model used in W_PFC. This approach would be linked to equilibrium PCS enhancements investigated in R18-1/1-G4 and reduced models investigated in R18-1/2-G5. Under this approach, the existing diagnostics in the SRD are assumed (plasma TV and thermocouples) and the design of a simple P_{RAD} diagnostic is outlined.

<u>GOAL-2: Describe monitoring approach that uses optical (NIR/IR) measurements to determine if an NSTX-U discharge is approaching temperature limits</u>

Lead: TBD (ORNL if resources permit)

Deliverable: PFC monitoring plan describing monitoring goals and approach (NIR/IR imaging)

Description: A more routine approach to PFC monitoring is to directly measure the infrared emission from surfaces as temperatures are elevated and relay information to the PCS for feedback control or discharge termination. This approach would be aligned with existing demonstrations on metallic devices and may also service physics research goals. The plan would describe number and placement of cameras, taking into account NSTX-U port access as well as describe the benefits of spectral range choices.

This approach would be linked to imaging PCS enhancements investigated in R18-1/1-G5 and reduced models investigated in R18-1/2-G5.

GOAL 3: Demonstrate pathway for sub-surface, temperature measurements to validate heat flux model

Lead: UT-K (Looby) [Masters Thesis Project]

Deliverable: NSTX-U report detailing findings

Description: A conservative monitoring approach would likely only be able to rely on embedded TCs within the high heat flux tiles, but there is limited information that will be available. Only the total rise in temperature after the shot is required by the diagnostic and it is expected to be sufficiently below the surface as to observe only 100-200 degC. It will also integrate over the spatial domain of a castellation. Sufficient shots with limited spatial scans of the heat flux profile while at low power and duration may allow the important parameters of the heat flux profile used in W_PFC (or equivalent) to be derived.
(STAGE 1): Assume an Eich profile with a chosen scaling of S and λ_q with engineering parameters and an angle of incidence of 2 degrees. Assume four divertors with a given inner/outer and upper/lower divertor sharing. Show that with perfect sub-surface temperature information, a limited number of shots with fixed and scanning heat flux profiles allow recovery of assumed model parameters for S, λ_q and power split.
(STAGE 2): Utilize advancements in pre-shot planning tools (R18-1/1-G2), final designs of PFC diagnostics and expected uncertainties in TC's shown in high heat flux testing (F18-1) to improve the demonstration. Include random and systematic error from TC's as well as expected redundancies as outlined in the PFC Diagnostics RD. Utilize realistic equilibrium and time-dependent sweeping to define surface heat flux through R18-1/1-G2 tools to more credibly describe a shot plan that can validate the unknown model parameters in W_PFC (or equivlent).

Record of Changes

Rev.	Date	Description of Changes
0	2/22	Initial draft release to PFCR-WG for comment